Detecting ν_τ Oscillations at PeV Energies

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Abstract

It is suggested that a large deep underocean neutrino detector, given the presence of significant numbers of neutrinos in the PeV range as predicted by various models of Active Galactic Nuclei, can make unique measurements of the properties of neutrinos. It will be possible to observe the existence of the ν_τ, measure its mixing with other flavors, in fact test the mixing pattern for all three flavors based upon the mixing parameters suggested by the atmospheric and solar neutrino data, and measure the nu_τ cross section. The key signature is the charged current ν_τ interaction, which produces a double cascade, one at either end of a minimum ionizing track. At a few PeV these cascades would be separated by roughly 100 m, and thus be easily resolvable in DUMAND and similar detectors. Future applications are precise neutrino astronomy and earth tomography.

1 The Double Bang Signal

In thinking about the consequences of τ production in DUMAND it has become clear that we may find a spectacular signature for τ events. This depends upon the existence of 10^{15} eV neutrinos in adequate numbers, as are in fact predicted from AGNs[1] for example. Since the τ mass is about 1.8 GeV, a τ of 1.8 PeV and with $c\tau$ of 91 μm[3] would fly roughly 90 m before self destructing. The interesting signals are from the charged current quark interactions of ν_τ's. The signature, as illustrated in Figure 1, is:

1. a big hadronic shower from the initial ν_τ interaction,
2. a muon like τ track, and then
3. a second big particle cascade (usually 3 times larger).

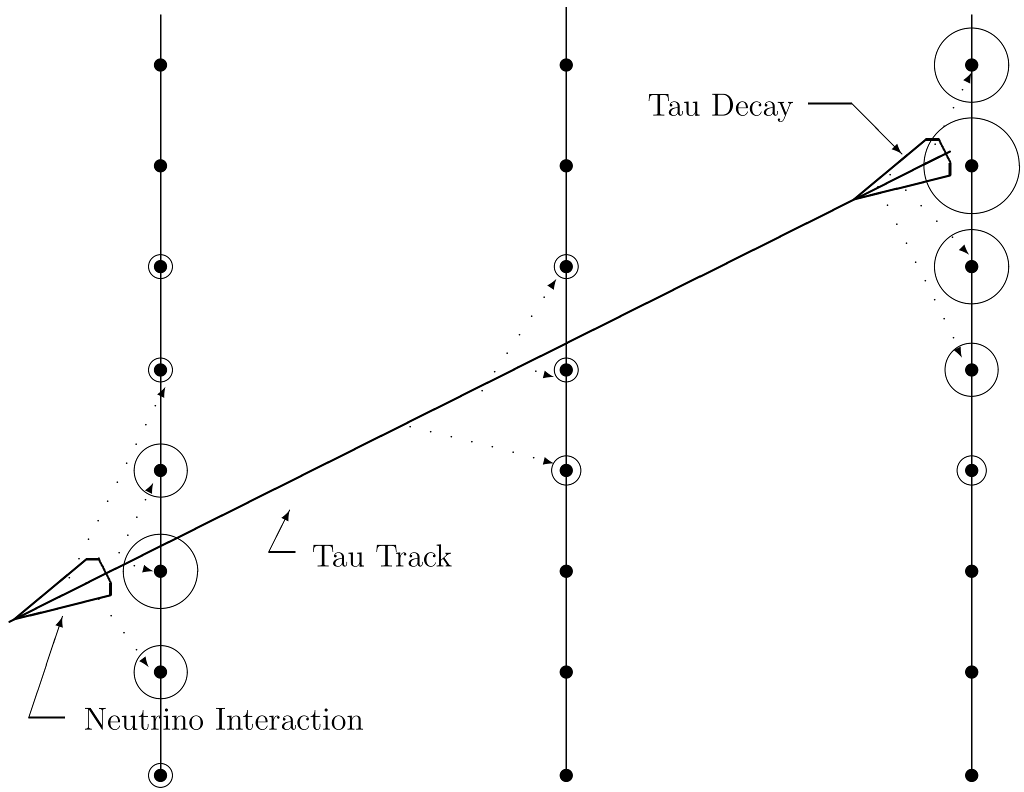

Figure 1: A schematic view of a "double bang" event near a deep ocean detector whose modules are indicated by dots.

To give some scale to this, the ratios of detectable photons from these three segments are roughly $10^{12} : 2 \cdot 10^{6} : 3 \cdot 10^{11}$.

The charged τ will be hard to resolve from the bright light and not very different times from the cascades, but simply connecting the two cascades by the speed of light will suffice to make an unambiguous association. This appears to be a unique signature for real τ production by ν_τ's, thus "discovering" the ν_τ, and infering the mixing angles for neutrino oscillations. Finding even one of these events would have significant implications.

The point is that in the general energy range of a few PeV there exists a powerful tool for searching for τ mixing, over an unequalled parameter space, with unambiguous identification of the τ. We know of no other way to make a ν_τ **appearance** experiment with the cosmic rays, no way has been

proposed for an accelerator experiment except for the use of emulsions making observations of relatively large δm^2, and no way of detecting ν_τ's except statistically at proposed long baseline accelerator experiments. (Indeed the costs of these endeavors are similar if one includes the preparation of the beams at the accelerators.)

In the following we explore the physics implications of the observations of the double bang events in a little more detail, discussing the kinematics, the sensitivity to two and three neutrino mixing, and potential backgrounds.

2 Essentially Full Kinematics from Double Bang Events

One gets to measure the total energy of the incident neutrino and nearly the full kinematics of the double bang events. The first cascade yields the energy transfered to the quark, and the second cascade gives the energy kept by the τ; the sum give the total incoming neutrino energy, and the ratio of the first cascade energy to the total energy provides the y value. The cross sections and $< y >$ are almost equal for ν_τ and $\bar{\nu}_\tau$ at this energy[4]. Observing the y distribution is a check on the observations, and departures from expectations could signal new physics. In calculating the ν_τ flux, the measured y distribution will permit correction for the potentially unobserved events near $y = 0$ (no initial cascade) and near $y = 1$ (initial cascade most of the energy and the tau decays too close for resolution). The near equality of the cross sections for particle and antiparticle permits the total flux to be calculated independently of the mix in the cosmic beam.

The threshold energy for discriminating two cascades will be determined by having a τ that flies far enough so that the two cascades can be distinguished, and so that there are no “punch through” events. This distance will be of the order of some few times the cascade length (order 10 m), and thus our threshold for τ detection via this means would be, as suggested above, about a PeV. With the physics limitation of several tens of meters, there will also be a detector dependent limitation depending upon detector density and response.

We note that the observation of the double bang events presents the opportunity to measure the PeV ν_τ cross section via the angular distribution

in the lower hemispere caused by attenuation through the earth ($\sim 90\%$ in this energy range). For future studies of earth tomography, the potential of this process is great, since it does not depend upon convolution over the y distribution and muon range, as is necessary to extract informatiom from the upcoming muon flux alone.

Also, given the enormous light output of the cascades one would expect that timing from the detectors (at intermediate distances, since nearby detectors of present design will surely be saturated) would give excellent vertex resolution, and thus the initial neutrino direction to a precision of order on 1°. In principle, of course, having both cascades and almost all energy "visible" one can deduce the initial neutrino direction with arbitrary precision, perhaps making optical precision ultimately possible in some future neutrino telescope.

3 Deducing the Neutrino Flux Flavor Content

From the ensemble of measurements with a DUMAND like array we will have:

1. The τ rate from double bang events gives the $\nu_\tau + \bar{\nu}_\tau$ flux.
2. Measuring the UHE muon flux permits calculating the $\nu_\mu + \bar{\nu}_\mu$ flux.
3. The W^- resonant event rate yields the $\bar{\nu}_e$ flux at 6.4 PeV.
4. Measuring the cascade rate (as a function of energy) gives the sum of neutral current interactions of all flavors of neutrinos and charged currents without visible μ's and τ's, that is mostly ν_e's.

If we write $r \equiv \sigma_{CC}/\sigma_{NC}$, the ratio of charged to neutral current cross sections, and we note that the cross sections are nearly flavor and charge independent at this energy, we can summarize the four observations abov as:

$$N_1 = N_\tau + N_{\bar{\tau}} \tag{1}$$

$$N_2 = N_\mu + N_{\bar{\mu}} \tag{2}$$

$$N_3 = N_{\bar{e}} \quad (3)$$

$$N_4 = (N_e + N_{\bar{e}}) \cdot (1 + r) + (N_\mu + N_{\bar{\mu}}) + (N_\tau + N_{\bar{\tau}}) \quad (4)$$

Combining these four equations we can then extract 3 flavor fractions ($f_e = (N_e + N_{\bar{e}})/N_{total}$, $f_\mu = (N_\mu + N_{\bar{\mu}})/N_{total}$, and $f_\tau = (N_\tau + N_{\bar{\tau}})/N_{total}$), and the antiparticle to particle ratio, $N_{\bar{e}}/N_e$.

We expect nearly equal numbers of particles and anti-particles, with half as many ν_e's as ν_μ's. In some scenarios there would be few ν_e's. The ν_τ flux from any source is expected to be very small in any case. Most predicted scenarios indicate adequate flight time for the π's and the μ's to decay at the source. In that circumstance there is only one free number in the initial flux ratios, the initial π^+ to π^- ratio.

The quantities to be observed do have different energy dependent sensitivity, which will complicate matters. We would expect that systematic uncertainties (in factors such as the effective volume, energy calibration, etc.) will be important in interpreting results. Detector specific simulations are needed to make explicit evaluations of these measurement possibilities. Nonetheless, it seems to us to be practical to extract the total flavor content of the cosmic flux with reasonable precision from this suite of observations.

4 Sensitivity to Neutrino Oscillations

Our δm^2 sensitivity (from L/E) is then fantastic, going down to the order of $10^{-16}\ eV^2$ (the distance is out to the AGNs, $\sim 100\ MPc$). To determine the two neutrino mixing angle sensitivity limit requires detector specific simulations. The limitation has to do with the AGN neutrino flux magnitude and effective volume for these events, and will probably be limited by statistics, at least in the near future. We guess it will be no better than 0.01 in the best of situations (as with most experiments).

To discuss the (to be observed) fluxes in terms of neutrino oscillations we make a number of simplifying (but reasonable) assumptions. Explicitly, we assume that:

1. the initial fluxes are in the proportion ν_μ:ν_e:ν_τ::2:1:0 (as generally expected),

2. there are equal numbers of neutrinos and anti-neutrinos (although this is not crucial and can easily be dropped in actual analysis),

3. all the δm^2 are above $10^{-16}\ eV^2$, and that $sin^2(\delta m^2 L/4E)$ all average to 1/2,

4. matter effects at the production site are negligible (this is reasonable since $N_{e^-} \simeq N_{e^+}$ and baryon densities are low), and

5. that there are no large matter effects in the path to earth. The latter is reasonable in the δm^2 range of interest (10^{-2} to $10^{-6}\ eV^2$).

With these assumptions, let us first consider the case where the low energy atmospheric neutrino anomaly is accounted for by neutrino oscillations. The oscillations could be either $\nu_\mu \leftrightarrow \nu_e$ or $\nu_\mu \leftrightarrow \nu_\tau$ with δm^2 of $10^{-2} - 10^{-3}\ eV^2$ and $sin^2 2\theta$ ranging from 0.5 to 1.0.

In both cases the ν_μ/ν_e ratio should be modified **exactly** as in the atmospheric case: given that the ν_μ/ν_e is found to be 0.6 of the expected value of 2, we expect exactly the same thing from the distant cosmic sources of much higher energy, ν_μ:$\nu_e = 1.2$:1. In the $\nu_\mu \leftrightarrow \nu_e$ mixing case this translates into ν_μ:ν_e:ν_τ::1.64:1.36:0 (using the earlier normalization to 3 total). In the other case, of $\nu_\mu \leftrightarrow \nu_\tau$ mixing, we predict ν_μ:ν_e:ν_τ::1.2:1:0.8. It is easy to see that in the two flavor mixing case, ν_e/ν_μ can never be greater than one. Even when the mixing is maximal on finds ν_μ:ν_e:ν_τ::1.5:1.5:0 in the $\nu_\mu \leftrightarrow \nu_e$ mixing case, and ν_μ:ν_e:ν_τ::1:1:1 in the $\nu_\mu \leftrightarrow \nu_\tau$ case.

We can now ask how expectations will change if we include neutrino oscillation solutions to the solar neutrino deficit. We can consider two distinct possibilities:

1. If the ν_e mixing with is with with either other species with a small angle, as in the small angle MSW regime, then the above results remain unaffected.

2. If all three flavors mix substantially and the δm^2's are in the range of 10^{-5} to $10^{-6}\ eV^2$ (corresponding to the MSW "large angle" solution) or $10^{-10}\ eV^2$ (corresponding to the "long wavelength" case).

The parameter space for a combined fit to the atmospheric and solar neutrino data has been given for each of the above cases by Fogli, *et al.*[7],

and by Acker, *et al.*[8], respectively. We have evaluated the survival and transition probabilities for the whole range of allowed values of the three mixing angles, and the results are shown in Figure 2. This figure plots the fraction of muon neutrinos versus the fraction of electron neutrinos, and thus where each point specifies a fraction of tau neutrinos (it is analogous to the color triangle). The initial expected flux (ν_μ:ν_e:ν_τ::2:1:0) is at $f_\mu = 0.66$ and $f_e = 0.33$.

We further observe that:

1. Amost all combinations of acceptable mixing angles result in saturation values to be observed with AGN neutrinos which lie between the lines $f_e + f_\mu = 0.88$ and $f_e + f_\mu = 0.66$. Hence a substantial number of ν_τ events are expected ($0.34 > f_\tau > 0.12$) for all situations which solve the solar and atmospheric problems with neutrino oscillations.

2. Since in the case of two flavor mixing it is impossible to obtain $f_e/f_\mu > 1$, observation of the data falling above the diagonal $f_e = f_\mu$ line is clear evidence for three flavor mixing.

5 Backgrounds: Almost None

We do not know of any particle with the ability to penetrate $\sim 10^4$ gm/cm^2 of matter before decaying or interacting (100 m is about 100 strong interaction lengths in water), except for leptons. Of the leptons, neutrinos have interaction lengths so great as to be negligibly likely to interact at close range ($< 10^{-6}$ at this PeV energy). Electrons will immediately radiate. Muons are the most likely to cause confusion. A muon of 2 PeV energy has a mean energy loss rate of 500 GeV/m, and an effective radiation length of about 1 m. Since on the order of 1/2 of the energy loss to the medium is continuous on the scale of a meter (it is a fuzzy number because of the continuous distribution of energy transfer fractions), the muon track light output will be roughly 1000 times minimum. Thus, even though muon radiation fluctuates greatly, we can anticipate that confusion with tau decays will be small. Once again, detector dependent simulations are required to numerically evaluate the confusion probability. Whatever that probability is, and we expect it to be low at 2 PeV, it decreases rapidly with energy (short range muon radiation goes up, and tau decay length increases). Finally, studies of the

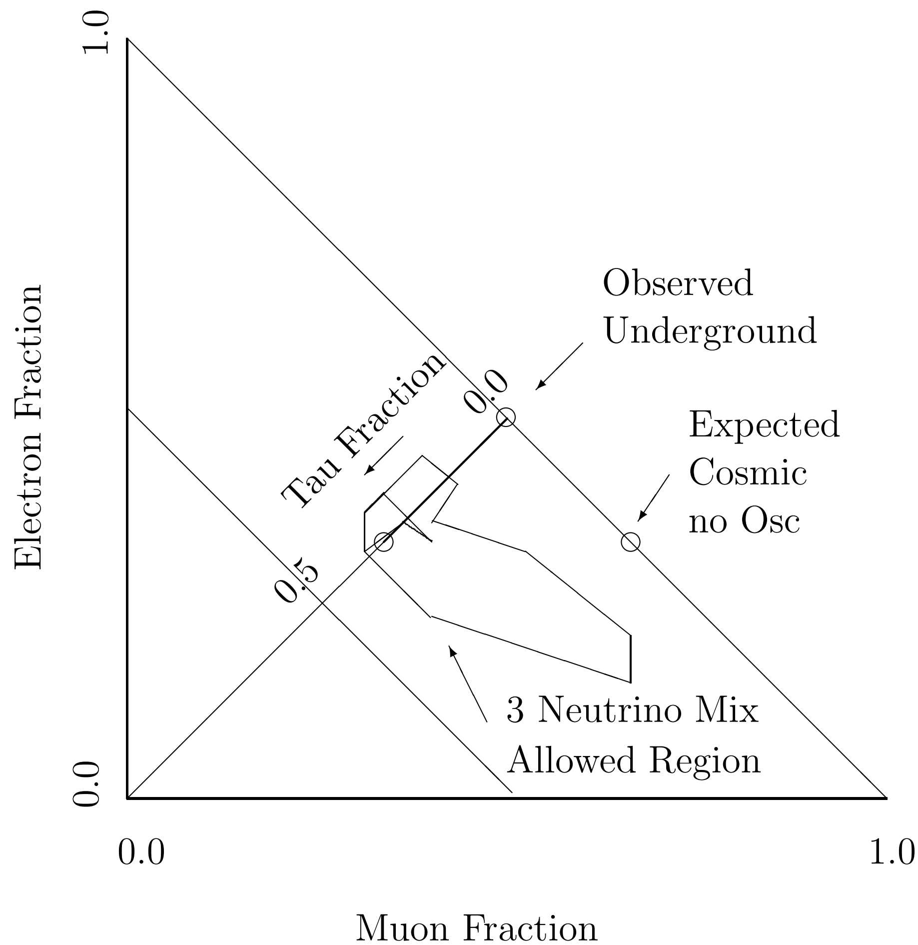

Figure 2: The fraction of muon neutrinos versus electron neutrinos, allowing for a fraction of tau neutrinos. The expected initial flux is at 0.66, 0.33. Full and equal mixing would result in 0.33, 0.33 (and 0.33 taus). The points represent calculations of results for various solutions to the solar and atmospheric neutrino problems.

path length distribution can confirm the observation of tau decays, requiring consistency with the known tau lifetime.

An other potential background might be due to downgoing muons. The downgoing muons are strongly peaked near the zenith, while the double bang events should be uniform in direction in the upper hemisphere, but heavily depleted from below the horizon by earth attenuation. A stronger constraint is that events with this energy are not expected from downgoing muons. Bremmstrahlung events of a few hundred GeV are plentiful, but the flux falls very fast with energy, and negligible numbers are expected above 100 TeV[5] (the radiation length for this energy muon is order of 20 m in water.). Thus even if one only had order of magnitude precision in cascade energy reconstruction (and we should have much better for near contained events such as we are discussing), one easily eliminates muons from the surface.

6 Old Idea, New Combination and Impact

The above is not entirely a new idea. Several authors have written about τ signatures in the past[6]. The new recognition is in coupling the uniqueness of the double bang signature, the encouraging flux predictions from AGNs, plus the modern hints about neutrino oscillations, and thus being able to make some claim as to the region we can probe in mixing space. Further we now recognize that observation of this novel class of interactions makes possible more precise measurements of the neutrino cross section and earth tomography than have been thought possible, because one can determine the *neutrino* total energy and direction with a precision limited only by the detector. For one thing, this potential observation does give motivation to filling in the volume, somewhat, of the hypothetical 1 km^3 array, and perhaps itself could justify construction of that experiment. Also, given that these events are near the acoustic detection threshold, one may contemplate hearing the double clicks from such events at km ranges and higher energies. (Bottom and surface reflected pulses might be thought to be a confusion factor, but in fact most often we would expect them to be useful as a tool for reconstructing range and orientation).

We remind the reader that all of the above requires the existence of substantial numbers of PeV neutrinos, which matter should be resolved in the next few years by the AMANDA, Baikal, DUMAND, and NESTOR exper-

iments now under construction. If those ultra high energy neutrinos are present in expected numbers, then we believe that the observation of the double bang events, along with other previously discussed interactions, will lead to important particle physics measurements which cannot be carried out in any other way on earth.

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